LIGHTWEIGHT, PRECISION, DEPLOYABLE STRUCTURES

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ABSTRACT

Future very large aperture telescopes will require the deployment of optical instruments with relative separations of 20 to 40m. These separations must be maintained with the same tolerances of the optical surfaces themselves. This paper discusses some of the anticipated design issues associated with the deployment of very large, ultra lightweight precision structures and describes a prototype developed to demonstrate the deployment of a large membrane support structure.

MOTIVATION

The key optical components of future space telescopes and interferometers must be deployed on orbit to provide the very large aperture required to resolve the planets of distant stars systems and the eventual discovery of signs of extraterrestrial life (1,2). The performance of such instruments will depend on maintaining the precision and stability of the deployed structural geometry to within nanometers of an ideal shape. Friction and freedom in the joints of deployed structures mean that deployed instruments will have the capacity to change shape at the micron and nanometer level of resolution (3). Eliminating such nonlinearities as friction and freeplay would enable a deployed structure to be as linear and precise as a monolithic block of material.

For traditional, rigid panel optics, deployed structures are required to provide a defined position relative to the optical prescription. Ultra lightweight, flexible optical panels have the additional need for reinforcing stiffness to reduce vibrational motion.

For large, membrane based optics, the boundary conditions at the edges of the membrane are critical to maintaining the desired shape of the reflecting surface. In current optical membrane ground testbeds (4), the outer edge of the membrane is supported by an optically ground ring. An on-orbit, large aperture membrane system would have to deploy a supporting ring of comparable precision.

EXISTING TECHNOLOGY

In most mechanically deployed structures, components are moved from their stowed positions into their final operational positions by some type of actuator and then locked into place with the same or an additional actuator (5). For high precision structures, it is critical that the load paths and load transfer mechanisms in the operational structure be linear and predictable for the reliable operation of the instrument.

The mass of traditional actuation and locking systems, as well as the mass of the electrical system required to power them, adds to the launch weight and thus increases the launch cost of the overall system. In addition, the verification analyses and testing of any deployment component are expensive and time consuming. For the complex, high precision components that are currently being developed, the verification and testing of deployment reliability is a process that is still being researched.

For high precision instruments, such as deployed telescope and interferometers, a simplification of the structure and a reduction in the number of components can both simplify the analysis and predictions of the systems performance and increase the linearity and accuracy of the deployed instrument.

ULTRA HIGH EFFICIENCY DEPLOYABLE STRUCTURES

To provide metering or stiffening structures for optical systems with 20 to 40m apertures, future deployed systems must be highly efficient. In this case, structural efficiency means a very large distance or area that is maintained with optical precision by a minimal mass structure.

For large separation distances (interferometers, metering of secondary optics), minimizing the mass dictates minimizing the cross section while maintaining strength and stiffness. For large collecting areas (primary segmented or continuous reflectors), minimizing the mass dictates minimizing the through-thickness. In both cases, the wall thickness is minimized to make maximum utilization of the material launch mass.

This low material thickness has substantial implications for structures in general and deployable structures in particular. By minimizing the thickness, the entire structure becomes more susceptible to surface area dependant phenomena. Since the thickness approaches that of thin shells, surface effects become structural effects. In addition, the low mass, and large spacing of such systems make them difficult to test on the ground because the mass and forces of the test apparatus tend to be large compared to that of the structure.

The large surface area of high efficiency structures also makes the optical instrument more susceptible to surface area dependant phenomena. These phenomena include, but are not limited to; micro-meteoroid/debris impact, off-gassing, surface chemical alteration, solar and rarefied gas pressure disturbances, and charged particle and EM field effects. The low thickness also exacerbates traditional structures issues by reducing the thermal and electrical conductivity.

Due to the low redundancy inherent to efficient structures, effects that reduce the local surface stiffness and strength, such as damage or alterations in material properties, have global structural consequences. Similarly, localized thermal gradients due to shadowing or differential heating can produce stresses resulting in a shift of the overall structural shape. Electromagnetic effects from exposure to charged particles or planetary magnetic fields can also produce structural interactions in addition to interfering with onboard electronics.

The testing, launch, and deployment of high efficiency structures produces an additional set of risks. Pre-launch testing of optical structures to ensure the telescope performance is complicated by the presence of gravity. Since gravity offload systems rely on the use of point loads to offset a distributed acceleration, they introduce artificial static and dynamic behavior. The deployment of structures on the ground introduces the possibility of damage and fatigue. The loads associated with launch and station delivery of a “Gossamer” structure must not introduce any wrinkles, kinks, or other localized weaknesses. Similarly, the final deployment of the structure cannot introduce changes in structural character that are beyond the bounds of on-orbit compensation.

All of the above concerns contribute for the need for deployment systems that are reliable both in the traditional sense of all deployment systems and in the sense of providing the desired positional and dynamic characteristics to within the bounds of planned adjustment and operation. This requirement for precision reliability will force the development of high efficiency deployed structures and mechanisms that are designed for their ground verification as well as for their on-orbit performance.

LIGHTWEIGHT DEPLOYABLE STRUCTURE DEMONSTRATOR

In order to explore some of the issues associated with the deployment of a large optical system, Foster-Miller developed a prototype lightweight deployable structure. The demonstrator consists of two independent structures that support a membrane primary reflector and a traditional secondary optic in a Cassegrain configuration.

The development of this prototype was a part of an overall investigation into the application of recent advances in manufacturing technology to the precision deployment of lightweight structures. This cost-conscious prototype was constructed to demonstrate an overall geometry that supported both the edges of a membrane primary reflector and the secondary optic from a central body representing the spacecraft instrument bus. Since this prototype was intended to demonstrate the structural aspects of the system, the membrane, the secondary and the central bus are placeholders rather than operational systems.

The technology that allows the structure to be stowed is a conceptual mid-point between traditional, rigid deployed structures and extremely thin, inflatable structures. Portions of the structure are constructed of a tailored material that allows the structure to be folded in a repeatable fashion. The result is a lightweight structure with stiffness and strength comparable to traditional aerospace structures.

The entire system is packaged into a roughly cylindrical volume, 2.9 ft (0.89m) in diameter and 6 ft (1.8m) tall. This volume fits within the payload envelope of the Pegasus Launch Vehicle, the smallest vehicle in the U.S. commercial launch fleet. This packaging configuration was designed for the kinematics of deployment and was not explicitly optimized for packaging efficiency. Figure 1 shows the packaged structure in the deployment test area.

The first half of the deployment is the raising of the secondary optic and its support structure. The support structure consists of a tripod with 15.5 ft (4.72m) legs, each of which is supported by a tripod connected to the base. During the deployment testing, a Helium balloon offloaded the secondary optic placeholder and the support structure. Figure 2 shows the secondary support structure in the deployed configuration with the primary system still stowed.

The second half of the deployment is the concurrent opening of the membrane primary and its support structure. The membrane is a polyethylene hexagon with a 14 ft (4.3m) diagonal. It is supported by a hexagonal perimeter structure, each corner of which is supported by a tripod attached to the base of the central bus. Figure 3 shows the final, deployed configuration of the prototype structure.

The completely deployed system has a collecting area of 127 ft^2 (11.8 m^2), or roughly 2.5 times that of the Hubble Space Telescope. The secondary is positioned 14 ft (4.3m) from the primary surface. The entire structure, including hinges, actuators, and latches but excluding the membrane and the secondary optic, has a mass of 19.3 lb (8.8 kg). The complete system shown in the above figures has a mass of 39 lb (17.7 kg).

The lowest vibrational mode of the structure is a torsional mode of the secondary tripod system and is estimated at 1 Hz natural frequency. The lowest mode of the primary structure is a "pancake" mode and is estimated at 15 Hz natural frequency. Since neither the stiffness of the structure nor the masses of the optics are truly representative of a flight system, these estimates should not be treated as indicative of an actual system dynamic behavior.

A similar style of structure, scaled up from the above design, would package into a Titan IVB shroud and deploy to a 20m diagonal primary aperture. This technology is not limited to this specific configuration and can be adapted to accommodate rigid panels or flexible, ultra lightweight reflectors.

The prototype deployable structure described above is a demonstration of technology in the early stages of development. Planned future work includes refinement of the manufacturing, incorporation into an actual optical system, and demonstration of the deployed precision, currently anticipated to be at the material behavior level.

CONCLUSIONS

The deployment and operation of ultra lightweight optics will require the deployment of comparably lightweight structures to provide precise metering of optical components and to augment the stiffness of the overall system. By the nature of their high efficiency, these structures will be extremely thin and thus highly susceptible to surface area dependant phenomena. This same "thinness" will also make surface damage and deviations in material properties due to stowage, delivery, and deployment significant to the on-orbit performance of the structure.

Technologies are currently being developed that may address some of these issues. A prototype structure has been constructed that uses foldable members to provide a 11.8 m^2 aperture and secondary optical support structure from the payload envelope of a small launch vehicle. However, significant issues such as the gravity offload testing of ultra lightweight optical systems must still be addressed.

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Figure 1. ***Prototype lightweight deployable structure in packaged state***

Figure 2. ***Prototype lightweight structure with secondary optic and support structure deployed***

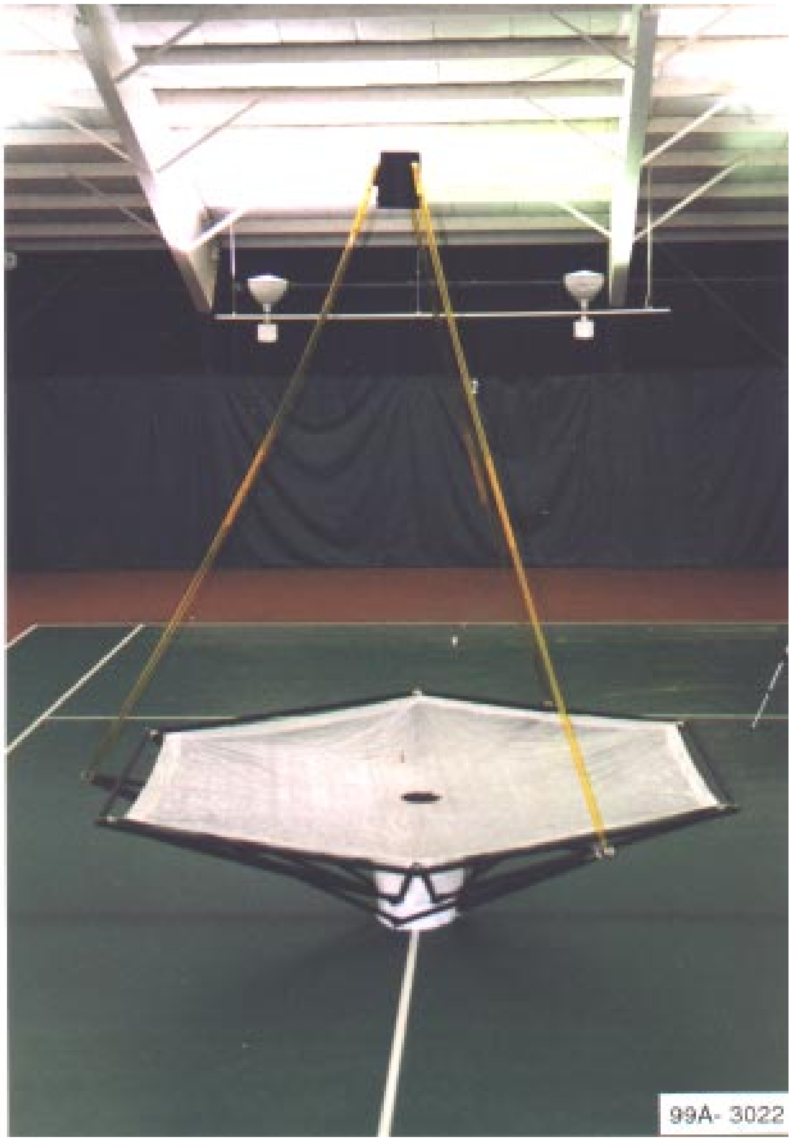

Figure 3. ***Completely deployed prototype lightweight membrane support structure***